Evaluation of Furniture-fire Hazard Using a Hazard-assessment Computer Model

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The Center for Fire Research Fire (Toxic) Hazard-Assessment computer model was used to evaluate the potential for hazard reduction by the modification of the combustion properties of upholstered furniture items in a residential occupancy. The potential benefits of these modifications are compared with the effects of variations in room size and construction to determine if they would be realized across a range of housing sizes and types. The results demonstrate the greatest benefit by the reduction of the mass loss (burning) rate of the item regardless of room size and even if the means used to reduce the burning rate results in an increase in smoke production and material toxicity. These results are intended as an indicator of potentially beneficial directions for further research and should not be taken as conclusive evidence of fact without experimental verification.

Editors' Note

As the author notes, the term 'Fractional Lethal Dose' is a smoke-exposure concentration level and not a dose in the usually defined sense. It not only fails to represent the fractional quantity retained by the animals but also requires the assumption of a 30-min exposure period which may or may not develop. The editors have accepted this paper because of its timely interest, but hope that this publication will not set a precedent for continued use of this term.

BACKGROUND

Over the past decade the field of computer fire modeling has been advanced to the point that reasonably accurate predictions of the consequences of fire in a structure can be made. While refinements in the capabilities of these models and validation of their predictive accuracy are the subjects of ongoing research, it is felt that they have advanced to the point that they can be used at least to provide comparative evaluation of hazard-mitigation strategies within their current limits of applicability. The purpose of this paper is to demonstrate how a specific hazard model might be used to identify the most promising hazard-mitigation strategy for a specific scenario of general interest.

Fires in residential occupancies accounted for some 80% of all civilian fire deaths, 70% of injuries, and 57% of property loss in calendar year 1983.[1] For the nation as a whole, statistics indicate that upholstered furniture is most often the first item ignited in fatal residential fires. Recognizing this fact, the furniture industry, through the Upholstered Furniture Action Council (UFAC), has developed and implemented a voluntary program intended to reduce the likelihood of the ignition of upholstered furniture items by dropped cigarettes.[2] While this program has been recently shown to be reasonably successful in reducing the likelihood of ignitions, it can never eliminate them, nor does it necessarily impact the likelihood of ignition from a flaming source nor the resulting hazard when any ignition occurs. In fact, thermoplastic cover fabrics which have good cigarette ignition resistance often exhibit a lower resistance to ignition by small flaming sources.[3] Thus, one logical step in making upholstered furniture safer might be to examine the potential benefits of material selection or modification in reducing the hazards of furniture fires given an ignition.

The hazards to building occupants from a fire involve the exposure to heat, toxic combustion products, and smoke which obscures vision and delays or prevents escape. The time available for the occupants to escape varies as a function of a number of parameters, only some of which can be controlled, in this case, by a furniture manufacturer. Thus the purpose of the following evaluation was to estimate the potential benefit of a variation in a controllable parameter relative to the variation which might be expected due to the parameters which cannot be controlled by the product-producer such as the room size or construction of the house into which the item is placed. By the use of relative comparisons, the effect of systematic errors due to the limitations in modeling capabilities should be minimized.

FIRE (TOXIC) HAZARD MODEL

The Center for Fire Research (CFR) has an ongoing project to develop quantitative methods for assessing fire and smoke* toxicity hazards based primarily on computer fire-modeling techniques. Recently, the first-generation hazard model developed by Walter Jones has been published.[4] This model (called FAST) can predict the generation, transport, and effect of heat, smoke, and a number of specific toxic gas species in up to eight

*The term smoke as used in this paper is defined by ASTM E176 to include all effluent fire products.

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interconnected compartments on a single floor of a structure. This is the hazard-assessment model used for the present evaluation. Details on this model and the CFR hazard-assessment program are contained in other published works[4,5] and will not be repeated here.

User-selectable input parameters to this model include the size and geometric relationship of the compartments in the structure, the thermal properties of the wall and ceiling materials used in the structure, and the combustion characteristics of the combustible contents (fuel). It is therefore a simple matter to vary any of these parameters individually or in combination and determine the effect on hazard, as will be seen later.

SCENARIO SELECTION

For the present case the basic scenario to be evaluated involves the combustion of a single piece of upholstered furniture exposed to a flaming ignition source in the living room of a single-floor residential structure. The interior finish was assumed not to become involved. This living room is at one end of a 9-m (30-ft) long hallway with a bedroom at the other end of the hallway (see Fig. 1). Only these three compartments were considered in the calculation, representing the case where any other compartments in the residence have tightly fitting, closed doors. For the base case, the room dimensions, construction materials, and geometric arrangements of the compartments were taken from an actual residential structure used in a series of smoke-detector experiments conducted in 1975.[6] The only exception was that the area of the living room was reduced by a factor of 2 for the base case since this actual structure had an unusually large living room. Since one of the varient cases examined was for a living room of twice the area of the base case, the actual structure was included in one of the cases examined.

In order to examine the impact of fire size, three upholstered furniture items were considered. These were an upholstered chair, loveseat, and sofa for which test data were obtained from Babrauskas.[7] These three items were

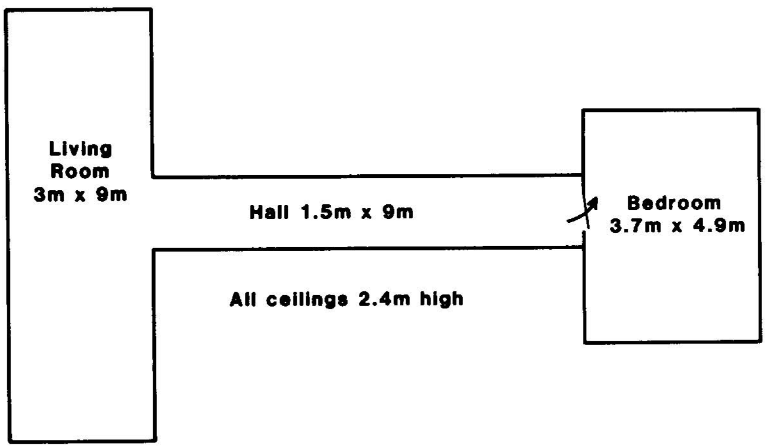

Figure 1. Floor plan for upholstered furniture hazard analysis based on "Lakeshore Residence" Reference 6.

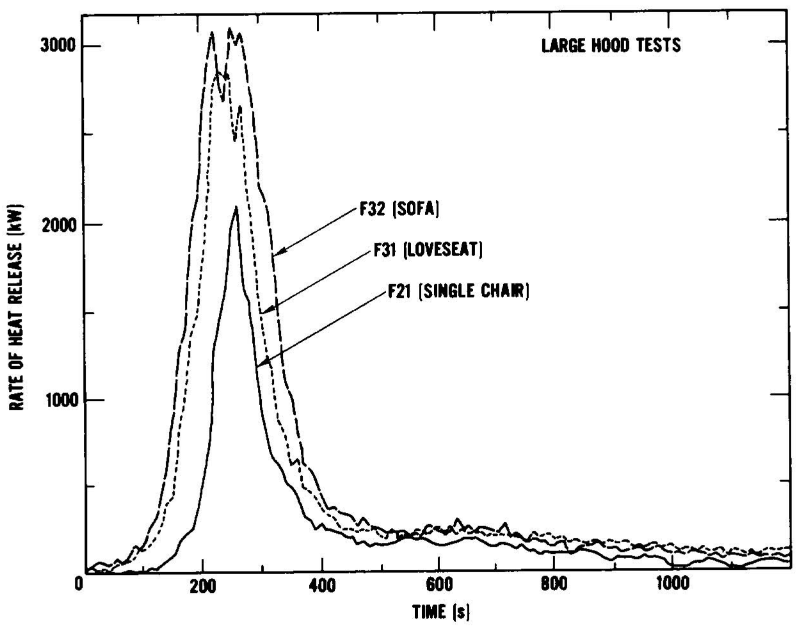

Figure 2. Heat release rates for the three upholstered furniture items.

actual furniture items acquired as a set and constructed of identical materials, varying only in size and mass. The heat-release curves for these three items are shown in Fig. 2. It was assumed that the burning behavior of these items was fuel rather than ventilation-controlled and would be the same in the room as was measured.[8] The input data used for the base case are detailed in Table 1.

After selection of the fuel items, these together with the parameter variations shown in Table 2 were used to construct the test matrix. As can be seen in the table, the varied parameters include the size of each of the compartments, wall material, and the effect of closing the bedroom door (which represent uncontrollable parameters from the perspective of the furniture manufacturer); and variation in fuel parameters include the heat of combustion, smoke release, and burning rate (which represent factors which can be controlled by the furniture manufacturer). Since the parameters were varied one at a time from the base case, this resulted in a total test matrix of 33 model runs.

Also examined for each case was the effect of increasing or decreasing the effective 'combustion product toxicity' of the furniture item. Due to the way this is calculated in the hazard model, this variation could be examined without the need for separate computer runs.

Table 1. Input data for the base case of the example

Burning item	Chair	Loveseat	Sofa
Heat of combustion (mJ kg^{-1})	18.1	18.1	18.1
Mass (kg)	28.0	40.0	51.0
Smoke yield (gg^{-1})	0.03	0.03	0.03
LC_{50} (mg l^{-1})	32.0	32.0	32.0

Room dimensions	Length (m)	Width (m)	Height (m)
Living room	9.0	3.0	2.4
Hall	9.0	1.5	2.4
Bedroom	4.9	3.7	2.4
Door opening to bedroom		1.0	2.0

Construction material properties	Walls (wood)	Ceiling (gypsum)
Thermal conductivity (kW m^{-1} K)	1.2×10^{-4}	1.7×10^{-4}
Density (kg m^{-3})	540	960
Specific heat (kJ kg^{-1}—K)	2.5	1.1
Thickness (cm)	1.59	1.59

Table 2. Parameter variation

	Base case
A	Double living room area
B	Halve hallway length
C	Double bedroom area
D	Gypsum board walls
E	Double heat of combustion
F	Halve heat of combustion
G	Double smoke fraction
H	Halve smoke fraction
I	Halve mass loss (burning) rate
J	Closed bedroom door (vertical crack $\frac{1}{4}$ in wide total)

HAZARD ANALYSIS

Once the parameter variation matrix had been established, the input files were created and the 33 model runs were batch-processed over one weekend. This produced 33 data files which are very similar to the data file produced by a data-acquisition system for a full-scale fire experiment. That is, the file contains values for each of the following parameters for each 10s of simulated fire time:

(1) Upper Layer Temperature;
(2) Lower Layer Temperature;
(3) Height (Above the Floor) of the interface between layers;
(4) Optical Density in the Upper Layer;
(5) Fractional Lethal Dose in the Upper Layer.

Each calculated parameter is essentially a bulk average value within a homogeneous layer, an assumption inherent in zone models. The 'Fractional Lethal Dose' represents the ratio of an exposure concentration to an exposure concentration which, if maintained over a 30-min period, was estimated to produce death in 50% of animals exposed. It is not a dose in the toxicological sense of the term since it does not directly consider uptake by the animal nor the period of exposure. The method of

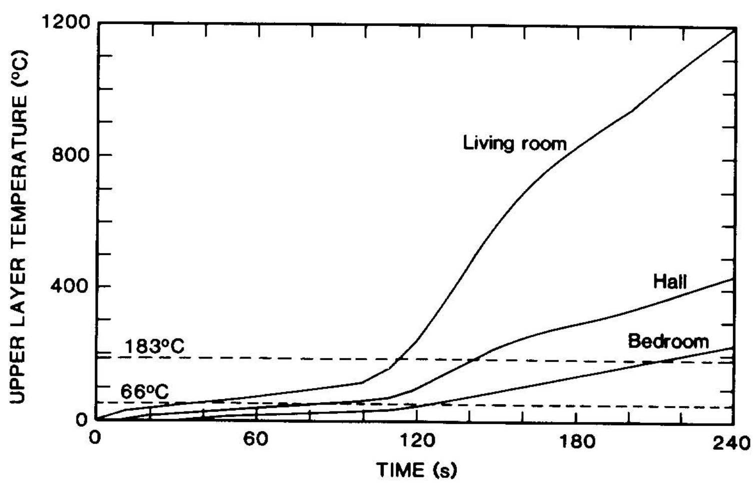

Figure 3. Example plot of upper layer temperature vs. time for base case, loveseat fire.

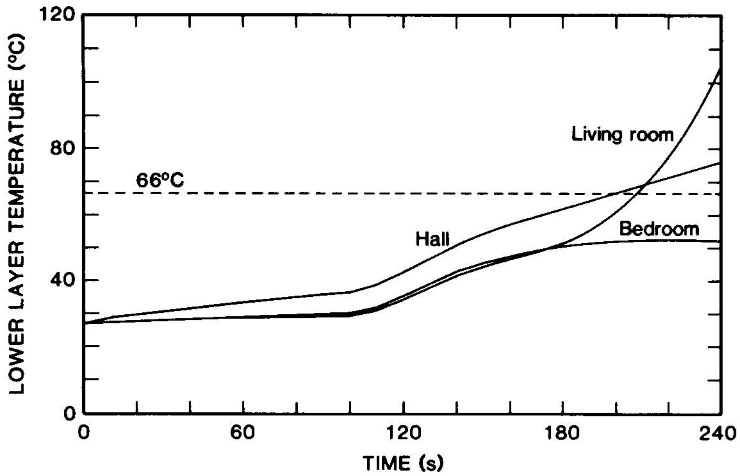

Figure 4. Example plot of lower layer temperature vs. time for base case, loveseat fire.

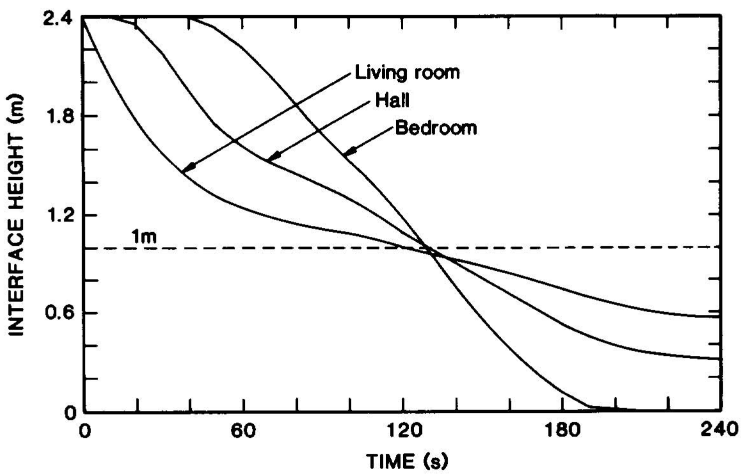

Figure 5. Example plot of interface height vs. time for base case, loveseat fires.

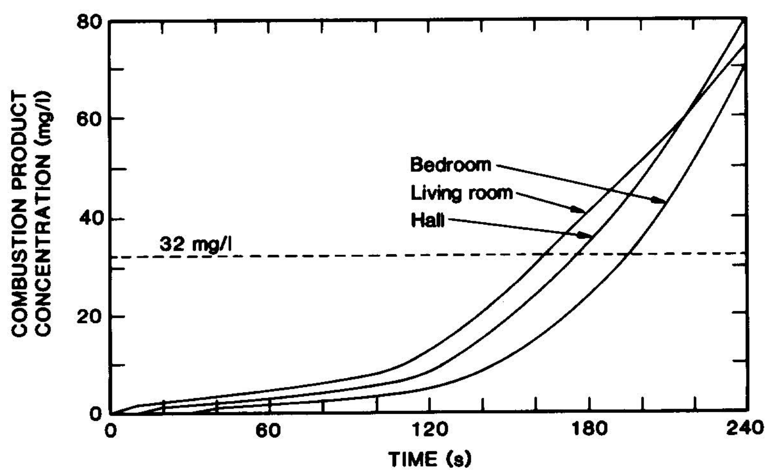

Figure 6. Example plot of upper layer toxicity concentration vs. time for base case, loveseat fire.

computation will be discussed later. Example plots of items 1, 2, and 3 for the base case, loveseat runs are presented in Figs 3–5. Figure 6 gives the toxic products mass concentration versus time for the same case; the fractional lethal dose would be obtained by dividing this concentration by 32 $mg\,l^{-1}$ for a 30-min exposure.

The model calculates a number of additional parameters which will not be discussed because they were not included in this evaluation. A complete discussion of all of the parameters calculated is included in the report on the model.[4]

The examined parameters are all straightforward except for the fractional lethal dose, which is described as follows.

The NBS Toxicity Test Method has been used to develop LC_{50} values for a number of simple materials. This LC_{50} is the mass of fuel loaded into the combustion chamber divided by the volume into which the combustion products are released, for which 50% of the test animals exposed to these combustion products died during either the 30-min exposure period or a 14-day post-exposure observation period. A thorough discussion of the test method and procedures is contained in reference 9.

Currently, data are available only on individual materials. However, the upholstered furniture items considered in this evaluation are constructed of a synthetic upholstery fabric, polyurethane foam, and a wooden frame. Therefore, an effective LC_{50} was calculated by taking estimated LC_{50} values for the fabric, foam, and wood and calculating a 'mass weighted average value' as follows:

$$\frac{1}{LC_{50}} = \sum_i \frac{f_i}{LC_{50_i}}$$

where f_i is the fraction of the total item mass represented by material i and LC_{50_i} is the 30-min LC_{50} of material i.

Since for all three furniture items the wood frame was about 25% of the total mass, the foam about 65% of the mass, both items exhibiting an $LC_{50} \sim 40\,mg\,l^{-1}$, and the fabric the remaining 10%, $LC_{50} \sim 12\,mg\,l^{-1}$, the effective LC_{50} used for each furniture item was $\sim 32\,mg\,l^{-1}$. While it is recognized that LC_{50}'s are not necessarily additive, this is the only means currently available to deal with multiple materials. For a discussion of the steps being taken to address this problem, see reference 5.*

The model then calculates a fractional lethal dose at any given time by taking the total fuel mass lost to that point in time, distributing that mass into the three compartments consistent with the complex flow phenomenon a contained in the model, and then dividing by the volume of the upper layer to obtained a mass concentration. The fractional lethal dose is then simply this computed mass concentration divided by the effective LC_{50} (32 $mg\,l^{-1}$ in this case) for a 30-min exposure period.

*It should be noted that this basis of comparison would not be strictly valid even if only a single homogeneous material were involved in the fire. This results from the fact that the test used reports LC_{50} values on the basis of material mass exposed, while the smoke concentration calculated is based on the specimen mass loss accumulation remaining in the upper atmosphere in the form of smoke. Nevertheless, for the purpose of this study the approximation involved seems justified.

The next step in the analysis was selection of hazard criteria. For each of the calculated conditions, two or three values were selected as representing limiting conditions for that parameter. Some people may argue with the values selected, but because the evaluation was done on a comparative basis, selecting different hazard criteria in most cases should have only a minimal effect on the relative results. Human tolerance to anything varies widely, and other values might be appropriate for other purposes depending on the projected capabilities of the occupants and the degree of conservatism desired. In any case, the values used in this evaluation are:

(1) Temperature: 66 °C and 100 °C;
(2) Interface Height (from the floor): 1.5 m and 1 m;
(3) Optical Density: 0.25 and 0.5 m^{-1};
(4) Fractional Lethal Dose: 0.5, 1.0, and 1.5.

For each of the 33 model runs conducted the time to reach each of these hazard criteria in each of the compartments was tabulated. The percentage change from the base case (+ or −) for each of these times was then calculated. These data for the chair simulations are presented in Table 3. The percentage change from the base case for each calculated condition gives an assessment of the value of the change of that parameter relative to both the base case and to each other. This allows both estimates of the hazard-reduction potential for controllable parameters and a method of comparing them with the variation which might be expected from variations in uncontrollable parameters.

RESULTS

A narrative discussion of the trends observed in the data relative to the base condition follows, for each of the cases studied. Cases involving parameters which would not be controllable by the manufacturer of an upholstered furniture item will be discussed first.

Doubling the area (and hence the volume) of the living room produces a small positive effect (longer time to reach critical conditions) for the upper and lower layer temperatures, optical density, and fractional lethal dose. The effect on the time at which the lowering interface height becomes hazardous is also positive and somewhat greater in magnitude. In all cases, these effects tend to be either the same or slightly greater for the larger combustible items and slightly smaller in magnitude for the bedroom compared with the living room.

Reducing the length of the hallway by a factor of two results in less time to escape for all hazard criteria examined except for the lower layer temperature, which did not rise as quickly. The magnitude of all of these changes was relatively constant for all three compartments and independent of the size of the combustible item.

Doubling the area of the bedroom had a small positive effect on all parameters (particularly in the bedroom), the magnitude of which was relatively consistent with fuel mass.

Changing the wall materials from a wood paneling to a gypsum board had no measurable effect on any of the calculated parameters compared with the base case. This

Table 3. Time to reach indicated condition and percentage change from base case for chair fires

Limit	Upper temperature Living room 66 °C		100 °C		Upper temperature Hall 66 °C		100 °C		Upper temperature Bedroom 66 °C		100 °C	
	s	%	s	%	s	%	s	%	s	%	s	%
Base*	106	—	119	—	124	—	140	—	149	—	178	—
A	115	8	128	8	135	9	152	9	162	9	199	12
B	106	0	118	−1	119	−4	133	−5	141	−5	165	−7
C	106	0	119	0	123	−1	138	−1	155	4	191	7
D	106	0	119	0	124	0	140	0	149	0	178	0
E	17	−84	106	−11	109	−12	123	−12	129	−13	149	−16
F	119	12	133	12	140	13	163	16	175	17	219	23
G	106	0	119	0	124	0	140	0	149	0	178	0
H	106	0	119	0	124	0	140	0	149	0	178	0
I	229	116	254	113	263	112	310	121	316	112	396	122
J	28	−74	66	−45	79	−36	119	−15	199	34	290	63

Limit	Lower temperature Living room 66 °C		100 °C		Lower temperature Hall 66 °C		100 °C		Lower temperature Bedroom 66 °C		100 °C	
Base	249	—	289	—	229	—	700	—	—	—	—	—
A	298	20	—	—	590	158	—	—	—	—	—	—
B	256	3	303	5	421	84	—	—	—	—	—	—
C	254	2	288	0	—	—	—	—	—	—	—	—
D	248	0	287	−1	228	0	710	1	—	—	—	—
E	205	−18	231	−20	64	−72	485	−31	—	—	—	—
F	430	73	—	—	511	123	—	—	—	—	—	—
G	249	0	289	0	228	0	700	0	—	—	—	—
H	249	0	289	0	228	0	700	0	—	—	—	—
I	531	113	617	113	628	174	907	30	—	—	—	—
J	141	−43	184	−36	141	−38	188	−73	—	—	—	—

Limit	Interface height Living room 1.5 m		1.0 m		Interface height Hall 1.5 m		1.0 m		Interface height Bedroom 1.5 m		1.0 m	
Base	45	—	146	—	110	—	154	—	128	—	152	—
A	85	89	180	23	133	21	180	17	153	20	172	13
B	39	−13	135	−8	100	−9	145	−6	119	−7	143	−6
C	44	−2	206	41	112	2	202	31	149	16	182	20
D	45	0	146	0	110	0	154	0	128	0	152	0
E	35	−22	125	−14	88	−20	135	−12	113	−12	136	−11
F	60	33	174	19	124	13	175	14	144	13	172	13
G	45	0	146	0	110	0	154	0	128	0	152	0
H	43	−4	146	0	110	0	154	0	128	0	151	−1
I	60	33	205	40	148	35	253	64	171	34	252	66
J	35	−22	111	−24	60	−45	89	−42	163	27	199	31

Limit	Optical density Living room 0.25 m^{-1}		0.5 m^{-1}		Optical density Hall 0.25 m^{-1}		0.5 m^{-1}		Optical density Bedroom 0.25 m^{-1}		0.5 m^{-1}	
	s	%	s	%	s	%	s	%	s	%	s	%
Base	107		126		124		143		144		165	
A	116	8	139	10	135	9	155	8	157	9	179	8
B	105	−2	126	0	118	−5	134	−6	138	−4	159	−4
C	107	0	126	0	123	−1	141	−1	148	3	169	2
D	107	0	126	0	124	0	143	0	144	0	165	0
E	111	4	130	3	124	0	143	0	141	2	162	−2
F	102	−5	123	−2	121	−2	143	0	145	1	168	2
G	21	−80	107	−15	65	−48	123	−14	115	−20	144	−13
H	126	18	149	18	143	15	166	16	165	15	192	16
I	229	114	265	110	258	108	299	109	288	100	334	102
J	31	−71	70	−44	59	−52	103	−28	148	3	170	3

Table 3. (*Continued*)

Limit	FLD Living room 0.5		1.0		1.5		FLD Hall 0.5		1.0		1.5	
Base	154		197		235		171		213		241	
A	172	12	225	14	258	10	189	11	233	9	265	10
B	154	0	197	0	232	4	167	−2	211	−1	237	−2
C	153	−1	193	−2	228	−3	165	−4	202	−5	233	−3
D	154	0	197	0	135	−43	171	0	213	0	241	0
E	163	6	216	10	251	7	175	2	217	2	244	1
F	149	−3	183	−7	215	−9	170	−1	208	−2	236	−2
G	154	0	197	0	235	0	171	0	213	0	241	0
H	154	0	197	0	235	0	171	0	213	0	241	0
I	330	114	440	123	512	118	370	116	450	111	506	110
J	127	−18	159	−19	183	−22	139	−19	162	−24	179	−26

Limit	FLD Bedroom 0.5		1.0		1.5	
Base	197		232		256	
A	214	9	257	11	287	12
B	190	−4	226	−3	250	−2
C	204	4	242	4	271	6
D	197	0	232	0	256	0
E	195	−1	229	−1	252	−2
F	200	2	235	1	260	2
G	197	0	232	0	256	0
H	197	0	232	0	256	0
I	401	104	471	103	519	103
J	205	4	236	2	257	0

[a] Refer to Table 2 for parameters

is because of the fact that wood paneling has very similar thermal properties to gypsum board, and both were assumed not to contribute to the fire.

Closing the door to the bedroom during the fire (but allowing some leakage) tended to produce a small to moderate positive effect within the bedroom with a small negative effect in the other two compartments. As one would expect, the closed (but leaky) door delayed the entrance of heat and smoke into bedroom. Conversely, the decrease in the remaining volume into which the mass and energy being released by the fire could spread decreased the time to hazard in the other compartments.

Summerizing the effect of the uncontrollable parameters, it can be seen that increasing or decreasing the size of the compartments produced positive and negative effects, respectively, on the time to reach hazardous conditions. The most important observation is that the magnitude of these effects tends to be small (of the order of 10–15%) for changes in area of a factor of two. Thus, if variations in controllable parameters produce more than a 10–15% increase in time to hazard, the benefit of such a change would be experienced regardless of the residence in which the item is used, assuming that the room sizes will not vary by much more than a factor of two in most cases. With this in mind, it is possible to discuss the effects of the parameters which can be controlled by material selection or modification.

The heat of combustion of a material is a measure of the potential energy released when burned, and is not a property which can be modified. A furniture manufacturer can, however, select a different material with a different heat of combustion. Either increasing or decreasing the heat of combustion by a factor of two produced small changes in the hazard time associated with interface height, optical density, and fractional lethal dose. For upper and lower layer temperatures, however, the observed effect on time to hazard was moderate (increasing for decreasing the heat of combustion and decreasing for increasing the heat of combustion). This is a reasonable result, since the heat of combustion would be expected to affect temperature directly with a secondary effect on interface height from the reduced buoyancy of the gases in the upper layer.

Conversely, variations in the smoke yield of the material shows no effect on the upper and lower layer temperatures, interface height, and fractional lethal dose. It did have a small to moderate effect on the time to reach a critical value of optical density. This smoke fraction is the fraction of original fuel mass which is released into the air as smoke, and is a parameter which can be modified by use of 'low smoke' materials. Some work is being done on smoke-suppressant chemical additives, but their performance is yet to be clearly demonstrated. Of more importance to the current consideration is the fact that the addition of fire-retardant chemicals to retard a material's burning rate sometimes has the effect of increasing the smoke yield of the material. In fact, changes in the smoke mass concentration in the upper layer will have an effect on the temperature since more mass will absorb radiant energy, raising the layer temperature. The current version of the model does not include this effect. From experimental data it is felt that the impact of inclusion of absorption would not change the conclusions of this analysis.

The final parameter variation was a reduction in the mass loss (burning) rate. In the present case the mass loss rate was decreased by a factor of two but the total burning time was doubled, so that the total energy released was the same as the other cases. This would typically be done by selection of materials that have inherently slower burning rates or by the addition of fire-retardant chemicals and inert fillers to a given material, although the amount necessary to be effective is generally large. In this analysis, this parameter was clearly the most desirable parameter evaluated in terms of its beneficial effect on hazard times. It produced a large (a factor of two to three times) increase in time to hazard due to upper and lower layer temperature, optical density, and fractional lethal dose, with a moderate (approximately 50%) increase in time to hazard due to interface height. For this case, the net gain is so much greater than for any of the other parameters that a net positive effect would be expected, regardless of the size of the rooms, and even if the fire-retardant chemical or optional material used produced twice as much smoke and was twice as toxic.

In summary, the evaluation described herein results in the following observations:

(1) Variations in room size by a factor of two produced small changes in hazard time, generally less than a 50% change relative to the base case.
(2) A closed bedroom door increased time to hazard within the bedroom on the order of 30–60% (which will vary with the crack size assumed), but decreased time to hazard in the other rooms due to the smaller volume into which the mass and energy is distributed.
(3) Variations in heat of combustion and smoke fraction produced small changes in time to hazard from temperature ($<60\%$) and interface height ($<25\%$); and visibility ($<60\%$), respectively.
(4) Decreasing the mass loss (burning) rate by a factor of two produced a large increase in time to hazard (100–200%) for temperature, smoke density and toxicity, and a small (30–70%) increase in time to hazard from interface height.

CONCLUSIONS

It was also noted that the time to reach hazardous conditions in these model predictions was consistant with that observed in the actual, full-scale experiments conducted by burning single items of upholstered furniture in the house from which the room geometries were taken.[6]

The hazard analysis procedure described here is intended to demonstrate how hazard models currently under development can be used to evaluate the potential benefits of and identify research priorities for reducing fire hazards and losses. Until these models are validated, their results should not be considered quantitative but rather should be used to identify promising areas for further research. With this as a guide, materials producers and furniture manufacturers can explore new materials and techniques and verify the benefits through more traditional small- and large-scale fire-testing programs. Eventually, as these models become statistically validated, it may be possible to obtain quantitative information with sufficient confidence to require little or no proof testing. For now, it is hoped that this paper has demonstrated the benefit of using these models to narrow the field of potential hazard-reduction strategies to those which can be expected to provide the maximum benefit.

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